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A renewable energy solution for Highfield Campus of University of Southampton

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ABSTRACT

In today's world where the global warming is one of the biggest problems for mankind, sustainable energy generation is becoming more and more important every day. This project focuses on the Highfield Campus of the University of Southampton and aims to achieve a more sustainable way of heat and electrical energy generation in order to help protect the environment.

The electrical energy to the Highfield Campus is provided from the national grid which primarily burns fossil fuels whereas the heat energy is mainly obtained by burning natural gas. None of these methods are sustainable and are major sources of greenhouse gas emissions. As the project objective, more sustainable ways of energy production in the campus are investigated, analysed and discussed in this report.

For this purpose, data acquisition is done by obtaining the energy consumption figures of the buildings within the campus. On the other hand, feasibility studies for various types of renewable energy sources are conducted revealing their potential contributions and applicability. All the data are then worked through to design more sustainable energy systems sticking to the project aims.

The resultant electrical and heat energy generation designs satisfy the project objective by utilizing alternative energy sources and reducing the greenhouse gas emissions of the campus, even though not in huge amounts. The results obtained are satisfactory in the sense that the proposed designs are both technically and economically feasible.

To conclude, these designs proposed in this project can be the first steps toward a more sustainable campus and get even more tempting with relevant technological improvements in the future.

Contents

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Nomenclature

T_c temperature of the cell (°C)
T_a temperature of the ambient air (°C)
NOCT normal operating cell temperature (°C)
G irradiance (W/m^2)
$I_{SC}(G)$ short circuit current at certain irradiance (A)
$V_{OC}(SC)$ open current voltage at standard conditions (V)
N_{cells} number of cells in the solar module
FF fill factor (%)
P_{max} maximum power (W)
η_{panel} efficiency of the panel (%)
A_{panel} area of the panel (m^2)
$A_{windows}$ the area of the windows (m^2)
$A_{p.doors}$ the area of the personal doors (m^2)
$A_{f.wall}$ the area of the front wall (m^2)
$A_{f.windows}$ the area of the front wall of windows (m^2)
$A_{r.wall}$ the area of the rear wall (m^2)
$A_{r.windows}$ the area of the windows of the rear wall (m^2)
$A_{s.wall\,1}$ the area of the side wall 1 (m^2)
$A_{s.windows\,1}$ the area of the windows of the side wall 1 (m^2)
$A_{s.wall\,2}$ the area of the side wall 2 (m^2)
$A_{s.windows\,2}$ the area of the windows of the side wall 2 (m^2)
A_{floor} the area of the floor (m^2)
A_{roof} the area of the roof (m^2)
M_{rear_wall} the empirical coefficient of ambient temperature at rear wall
M_{front_wall} the empirical coefficient of ambient temperature at front wall
$M_{side\_wall\,1}$ the empirical coefficient of ambient temperature at side wall1
$M_{side\_wall\,2}$ the empirical coefficient of ambient temperature at side wall2
$N_{windows}$ the number of the windows
$N_{p.doors}$ the number of the personal doors
$N_{f.windows}$ the number of the windows on front wall
$N_{r.windows}$ the number of the windows on rear wall
$N_{s.windows\,1}$ the number of the windows on side wall 1
$N_{s.windows\,2}$ the number of the windows on side wall 2
$N_{windows.direction}$ the number of the windows at the direction in question
$P_{windows}$ heat loss through the windows (W)
$P_{p.doors}$ heat loss through the personal doors (W)
$P_{f.wall}$ heat loss through the front wall (W)
$P_{r.wall}$ heat loss through the rear wall (W)
$P_{s.wall\,1}$ heat loss through the side wall 1 (W)
$P_{s.wall\,2}$ heat loss through the side wall 2 (W)
P_{floor} heat loss through the floor (W)
P_{roof} heat loss through the roof (W)
$P_{n.vent}$ heat loss by natural ventilation (W)
$P_{total\ loss}$ total heat loss through building in question (W)
P_{sg} solar gain as a function of month and direction (W)
$P_{occupancy}$ internal heat gain from occupants inside building in question (W)
$P_{lightening}$ internal heat gain from lightening inside building in question (W)
$P_{elec.}$ internal heat gain from electrical device inside building in question (W)
$P_{internal}$ total internal heat gain (W)
P_{total_gain} total heat gain (W)
P_{heat} total maximum heat requirement of building in question (W)
$U_{windows}$ the thermal transmittance coefficient of the windows (W/(m^2 K))
$U_{p.door}$ the thermal transmittance coefficient of the personal door (W/(m^2 K))
$U_{f.wall}$ the thermal transmittance coefficient of the front wall
$U_{r.wall}$ the thermal transmittance coefficient of the rear wall (W/(m^2 K))
$U_{s.wall\,1}$ the thermal transmittance coefficient of the side wall 1 (W/(m^2 K))
$U_{s.wall\,2}$ the thermal transmittance coefficient of the side wall 2 (W/(m^2 K))
U_{floor} the thermal transmittance coefficient of the floor (W/(m^2 K))
U_{roof} the thermal transmittance coefficient of the roof (W/(m^2 K))
T temperature differences between ambient air and inside the building (K)
ΔT_{soil} temperature differences between ambient soil and the floor (K)
ΔT_{SH} increase in gas temperature in suction line (K)
n number of air changes per hour (natural ventilation ratio)
$V_{building}$ the volume of the building (m^3)
$Sp.ht$ specific heat factor for air
$C_{p,air}$ specific heat capacity of air (kJ/(kg K))
P_{air} the density of air (m^3/kg)
S solar gain factor
q_{sg} mean solar load as a function of month and direction (W/m^2)

SHR	sensible heat ratio (%)
RH_{AIR}	relative humidity (%)
T_{AIR}	room temperature (°C)
Ψ	exergy (kJ/kg)
Ψ_i	exergy at the inlet port (kJ/kg)
Ψ_e	exergy at the exit port (kJ/kg)
h	enthalpy (kJ/kg)
s	entropy (kJ/(kg K))
T_0	the environment temperature (K)
$w_{in,min}$	the minimum work required to drive compressor (kJ/kg)
w_{actual}	the actual work (kJ/kg)
w_{rev}	the reversible work (kJ/kg)
η_{II}	the second law efficiency (%)
i	irreversibility (kJ/kg)
v	specific weight (kg/m^3)

1. Introduction

1.1. Introduction

Energy is one of the most fundamental parts of the universe. It is used to light the cities, power different types of vehicles, heat and cool homes as well as many more countless applications. In other words, everything people do is connected to energy in one way or another.

Since the industrial revolution took place between the 18th and 19th century, fossil fuels have emerged to be, and still are, the main source for supplying the energy needs of mankind. Various types of fossil fuels have significantly contributed to the success of many inventions mainly due to their flexibility and relatively high energy content in the different ways they can be utilized. Unfortunately, fossil fuels are non-renewable and, more importantly, cause pollution owing to their emission of harmful gases to the atmosphere. As a result of the dwindling supply of fossil fuels, people are eventually going to be forced to search for alternative energy sources to meet their energy demands. Sooner or later, renewable energy sources will have to be considered, harnessed and transformed into usable forms of energy. That is why there is dire need to know the options available and how to exploit them efficiently and effectively and above all consider the environmental concerns these energy sources give rise to. For this reason, it is urged that methods for improving the energy efficiency are contemplated and applied to buildings, as this can significantly reduce their energy demands. In that sense, the Highfield Campus in the University of Southampton is undergoing major transformations aiming to become a green campus.

New energy-efficient buildings have been constructed recently in the Highfield Campus. However, the true problem lies within the existing buildings, as most of them were relatively built a long time ago. This means that energy-efficient techniques were not applied to them; thus, increasing their energy consumption rates. One more problem is that the infrastructure of the Highfield Campus was old; therefore, sustainability and efficiency issues were not taken into account when it was placed decades ago. A group of students (the authors of this report) have set out to examine the Highfield Campus from different aspects and investigate the possibility of integrating different sustainability-related concepts to the buildings in it. With that in mind, the aims and objectives of this report are outlined in the next subsection.

1.2. Aims

There are plenty of sustainability concepts that can be suggested for utilization in the buildings of the campus; however, they cannot all be discussed in this report. Therefore, the authors decided to select two types of systems to be analysed and looked into, one for power generation and the other for heat generation. Those are photovoltaic (PV) systems and heat pumps. With that into account, the main objectives and aims of this report are listed as follows:

i. To develop a broad understanding of the basic principles of operation of PVs and heat pumps.
ii. To determine the energy consumption rates of different buildings in the campus for both heating and power.
iii. To present a design for each type of the selected systems to be integrated into selected buildings based on intensive analysis of different design aspects.
iv. To calculate the cost and the payback period of the suggested designs.
v. To ascertain whether the suggested designs meet the energy demands of the campus and whether it is economical and feasible to install them.

2. Background research

2.1. Photovoltaic systems

2.1.1. Overview

Solar radiation is an infinite energy source. In fact, it has the highest percentage of energy when compared to other types of renewable sources. Other renewable resources, such as wind and wave energy, are even derived from it. That is why solar radiation should be captured and used to produce forms of energy that deemed usable by mankind instead of continuing to use fossil fuels. Employing technologies that use solar power to generate electricity or heat without any pollution will surely help reduce the overall amount of greenhouse gases emitted into the atmosphere. Photovoltaic cells are perhaps one of the most known solar technologies. They involve the direct conversion of light into electrical energy. They are considered to be one of the leading systems for generating electricity in the 21st century due to their reliability together with the fact that they have no emissions.

When installed, individual PV cells are organized in modules, the modules in panels and the panels in arrays which can be connected either in series or in parallel; therefore, the alignment of the arrays affects the overall voltage, current and thus power level of the arrays.

The two major classifications of PV systems are on-grid and off-grid (or stand alone) systems. On-grid systems rely on directly feeding the national grid with whatever electricity they produce, with compensation of course. Off-grid systems are not meant to be connected to the national grid. That is why batteries are integrated in such systems. They are likely to be found in remote areas where electricity is not provided. In this project, off-grid systems are focused on as the energy produced is to be used instantly without being stored.

PV systems, also known as solar panels, are commercially established in the market. The most common types of PV cells are listed below:

- Single-crystal silicon cells (or monocrystalline).
- Polycrystalline cells (or multicrystalline).
- Ribbon silicon cells.
- Thin-film cells (amorphous silicon, copper indium diselenide cell, cadmium telluride cell, thin polycrystalline silicon cell grown on a low-cost substrate).

2.1.2. Principles of operation

PV panels are used for the generation of electricity. Their function is based on the direct conversion of sunlight into electricity (DC) with the use of junctions. Each junction is constructed by two semiconductors; typically, one is p-type and the other is n-type. The stages of the electricity production via PV cells are discussed below:

1. Sunlight hits the surface of the PV cells.
2. Sunlight irradiation causes electrons to separate from their atoms.
3. Electrons and holes begin to move toward the P–N junction.
4. When the electrons and holes come together at the P–N junction, a voltage potential is generated which results in a useful electric current.

The performance of the PV modules is rated according to their peak power output under standard test conditions (STC). Those are: operating temperature of 25 °C, spectral distribution of AM1.5 and an incident solar irradiance level of 1000 W/m^2 [1]. Irradiation, which depends in the geographical location, is an important factor that plays role in the production of electricity. Simply, electricity production increases as the irradiation increases. The capture of the sun rays from PV panels depends on both the solar azimuth and the solar declination. To maximize the amount of captured sunlight, a PV panel has to be perpendicular to the incident light falling on it [1]. In order to achieve this, sunlight tracking devices are needed to change the inclination of the panels accordingly. In this report, the case at which the panels are stationary is investigated. That is why it is chosen solar azimuth 0° and solar declination 36° to capture the maximum sunlight all around the year.

It was mentioned before that PVs generate direct current (DC). However, it has to be converted to alternating current (AC) before it can be connected to the mains. This is done by means of an inverter. The inverter oscillates the electricity produced until it matches the frequency of the grid. Although the conversion process results in some minimal energy losses, the efficiency of inverters can reach up to 95%, depending on the model used. Its operation also depends on the load as well as the outside temperature. Therefore, it is recommended that the inverter is placed in a relatively cool area.

2.2. Heat pumps

2.2.1. Overview

With the issues of the continuous rise in the cost of fuel and global warming at the vanguard of the world attention, the interest in utilizing heat pumps (HP) is growing more and more. This is because "it is the only known process that re-circulates environmental and waste heat back into a heat production process; offering friendly heating and cooling" [2]. HPs are capable of moving heat from one environment to another in either direction by using minimal amounts of energy. The HP is considered to be a mature technology, as it involves the efficient use of energy to obtain a reduction in net energy consumption. Upon this fact, studies have also shown that HPs have the potential to greatly reduce greenhouse gas emissions, particularly those of CO_2 [2]. That is why they are used in the heating/cooling of buildings as well as in various industrial applications.

There are two main types of HPs: compression HPs and absorption HPs. Compression HPs operate on mechanical energy, driven by electricity, while absorption HPs operate on a heat source, most commonly provided by burnable fuels. Compression HPs are more commonly used and more efficient than absorption HPs; however, absorption HPs emerge to be a more suitable option in remote areas where electricity is either not supplied or when it is more expensive than natural gas. For the suggested design, compression-type HPs are going to be used as they can achieve higher efficiencies than absorption-type HPs.

Compression HPs can either be aerothermal or geothermal. Both are discussed below:

1. Aerothermal means that heat is extracted from the air. HPs can be:

a. Air to air
b. Air to water

2. Geothermal means that heat is extracted from sources in the ground. HPs can be:

a. Ground to air
b. Ground to water
c. Water to air
d. Water to water

Whereas the first terms refer to the heat source and the second terms refer to the heat sink. Due to the relatively compact arrangement of the buildings in the Highfield Campus, air-source HPs are the most suitable ones to use, as they require little space both indoors and outdoors. The principles of operation of air-source compression HPs are discussed in the following subsection.

2.2.2. Principles of operation

HPs can be used for heating or cooling purposes. All compression HPs work on the vapour compression cycle when operated at cooling mode and on the reversed vapour compression cycle when operated at heating mode. An alignment of a compression HP along with a description of its different components and the way they operate is displayed in Fig. 1:

1. Heat is extracted from the earth, outdoor air or a geothermal water source. It is transferred from the source to either air or water in the pipe going to the evaporator. Air/water inside the pipe has the same temperature as the heat source.
2. The heat is then fed to the evaporator. An evaporator is a heat exchanger that allows heat to be transferred from the air/water coming from the source to a CFC-free working fluid (refrigerant), which is at low pressure. The refrigerant's temperature has to be lower than that of the air/water coming from the source for the transfer of thermal energy to take place. As a result of the heat transfer, the refrigerant gains heat and evaporates. However, it remains at low pressure.
3. The refrigerant vapour enters the compressor, where its pressure increases. Consequently, the compression process causes its temperature to increase. The compressor must be capable of providing a high pressure difference for a small mass refrigerant flow rate.
4. The high pressure refrigerant vapour then enters the condenser. The condenser is a heat exchanger that allows heat to be transferred from the pressurised refrigerant vapour coming from the compressor to the heating water. The vapour's temperature has to be higher than that of the heating water for the transfer of thermal energy to take place. As a result, the vapour rejects heat and condenses to a liquid. However, it remains at high pressure.
5. The heating water transfers its heat to the radiator/convector heating system which in turn gives it off for the room(s) to be heated. The heating water returns to the condenser to gain heat again and re-circulate back to the heating systems.
6. The high pressure liquid refrigerant then enters the expansion valve, where its pressure decreases. Consequently, the expansion

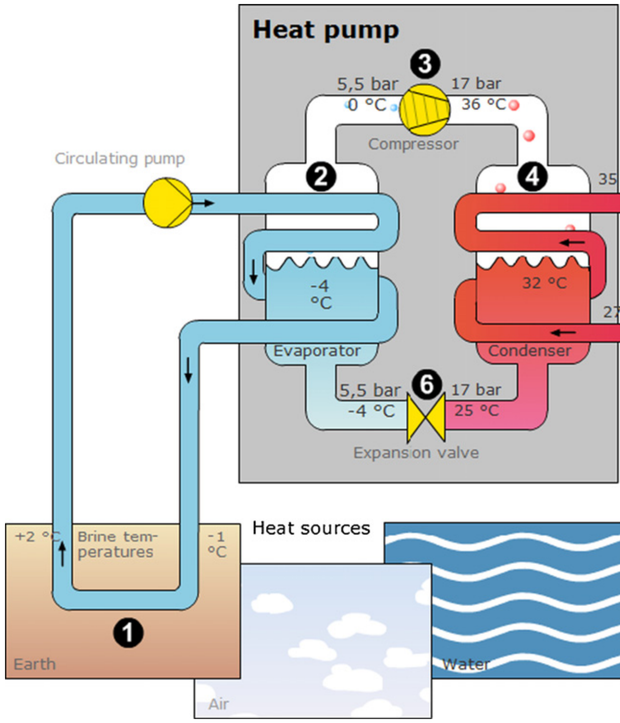

Fig. 1. A vapour compression HP operated at heating mode [5].

process causes its temperature to decrease. The liquid refrigerant now becomes a mixture of liquid and vapour at low pressure.

When HPs are operated at cooling mode, the same steps are used except that the evaporator is now the condenser and the condenser is now the evaporator. Heat is extracted from the cooled area(s) and rejected outside as waste heat. Some HP systems can be operated at both cooling and heating modes. In order to do so, they have to be equipped with a reversing valve.

When HPs are used in heating mode, the efficiency of the process is found by dividing the heat output, Q_H, by the electrical input of the compressor, W. Due to the heat recovery ability of HPs, high efficiency values are achieved. HPs are assessed by the coefficient of performance, or COP. HPs operating at cooling mode have a lower COP than those operating at heating mode; as the heat energy in the vapour is used for space heating in the heating mode while in contrast it is not used and dumped outside while operating in cooling mode. For air-source HPs, the COP of heating is typically around [3,4]. If the COP of a HP is 3, this means that it is 300% efficient and that for every 1 kWh of electrical input at the compressor, 3 kWh of useful heat output is given out. At this point, it is clear enough that the higher the COP, the more efficient a HP is. In the case of air-source HPs, the lower the outside temperature, the higher the temperature difference between the outdoor and the indoor unit; thus, more electrical power have to be inputted at the compressor in order to move enough heat indoors. For this reason, the heating COP of HPs and their performance decreases as the outside temperature decreases. It reaches up to a certain point where the HP stops working as running it would consume more energy than it would give out. This happens at a COP of 2 which is considered as the lower limit and the temperature at this point is known as the shutdown temperature. For this reason, HPs should always have a backup system, e.g. a boiler, ready to either operate at part load to compensate for its decline in performance before reaching the shutdown temperature or to operate at full capacity to be able to provide sufficient heating when the HP is not operating at very low temperatures.

3. Design procedure

3.1. Energy consumption in Highfield Campus

3.1.1. Overview

Being aware of how much heat and power is being consumed in the Highfield Campus is crucial because it guides the authors in the process of sizing the systems for their suggested designs (this is done at a latter stage of the report). Therefore, the first step throughout the project was to gather as much data as possible about the energy consumption in the Highfield Campus. In the following subsections, the acquisition of energy consumption data in addition to the infrastructure of the campus is discussed.

3.1.2. Energy consumption data

At the very beginning, the first thing done in order to acquire as much information as possible was to check the energy certificates and advisory reports of each building. Those provide information such as:

- Building description.
- Building environment (e.g. natural ventilation. Heating is provided by radiators/convectors).
- Total useful floor area.
- Main heating fuel (natural gas, district heating or electricity).
- Annual heating fuel energy consumption and percentage from renewable sources.
- Annual power consumption and percentage from renewable sources.
- Annual CO_2 emissions.

Such basic information provides an idea of how much energy each building consumes for heating and electricity purposes. More detailed information was acquired from the metering website of the university. This website contains every possible reading that is related to the energy consumption of the campus. For both electricity and heating, readings are provided on a half-hourly basis.

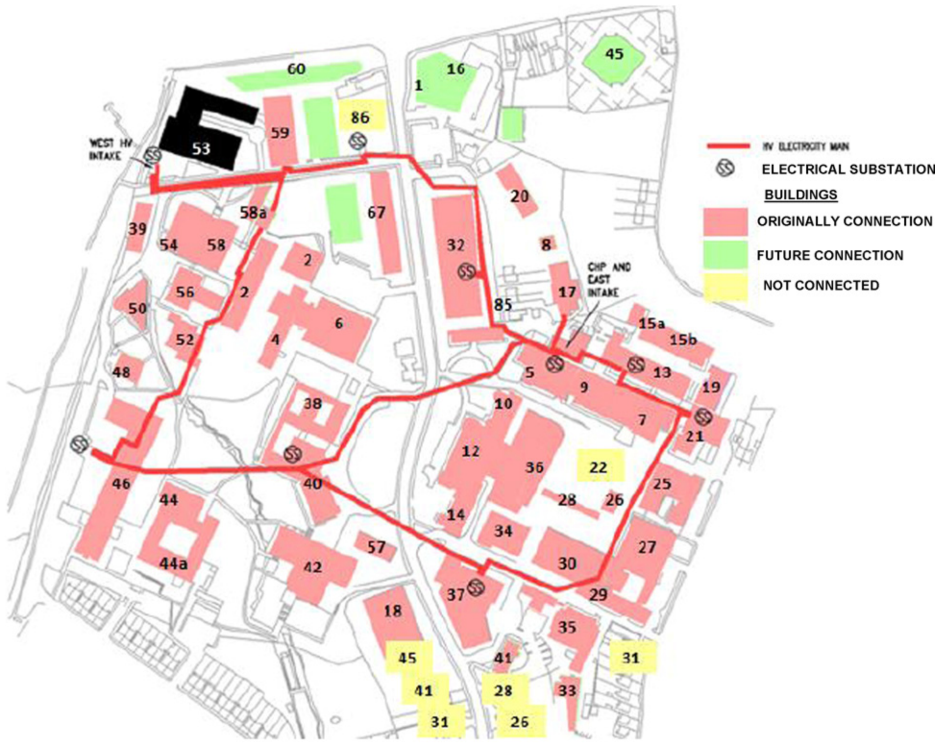

Fig. 2. CHP mini-grid for electricity [7].

Based on the data obtained from this website [6], 35,198.186 MWh of electricity and 27,362.384 MWh of heat was consumed in the Highfield Campus in 2009. This means that 4.02 MW of electricity and 3.12 MW of heat have to be generated on average to meet its energy demands. Ensuing to this relatively substantial consumption, 39,890.683 tons of carbon dioxide emissions were produced that year. This is a huge number and in order for the campus to become greener, a lot has to be done to reduce this number to an acceptable value.

By looking at the power vs time sets of data for several buildings, it was observed that the peak-demand time period lies between 10:30 am and 6 pm in weekdays while it is considerably lower in weekends. In the case of heat, it was found that the university consumes the maximum monthly amount of heat in February. This was based on the heat consumption data of the campus for the last four years. All in all, the exact requirements needed for designing and sizing the suggested systems were acquired from this website.

3.1.3. Electricity/heating infrastructure

Looking at the infrastructure maps of the campus revealed that most buildings are connected to a mini-grid that is linked up with a CHP plant on campus. This CHP plant was activated in November 2005 consequent to high consumption values of electricity and heat. The activation of this plant has helped to reduce the carbon emissions by about 2000 tons per year; however, this was obviously not enough considering the substantial amount of emissions mentioned before. Displayed in Figs. 2 and 3 are maps of the CHP mini-grid for both electricity and heat.

It can be seen in Fig. 2 that almost all buildings are connected to the electricity CHP mini-grid. In contrast, fewer buildings are dependent on the heating CHP mini-grid as they are in the case of electricity, as can be seen in Fig. 3.

Taking all the information mentioned in Section 2 into account, the authors have specified the following aims:

(1) Aim to provide as much as possible of the electricity demands for the entire campus by installing PV panels.
(2) Aim to provide the heat energy needs for selected buildings that are not connected to the heating CHP mini-grid by installing heat pumps. Those are buildings 1, 16, 22, 41, 45, 48, 57, 58a, 60 and 67.

3.2. Photovoltaic system design

3.2.1. Technical considerations

3.2.1.1. Choosing the most efficient solar panel. An in-depth investigation of several solar panel types from various manufacturers was conducted in order to choose one that has the highest power output. A list of tens of modules was prepared and the ones with the highest five efficiencies were then analysed and focused on to figure out their numerical power outputs in Southampton. In order to do that, the irradiance and temperature data of Southampton were obtained on a monthly basis and used in the appropriate calculations. Results revealed that the 240-PE model, which is manufactured by REC group, generates the highest amount of electrical energy per annum when compared to the others.

In order to calculate the power output of REC 240-PE, two different methods were used. The first method involved the calculation of the short circuit current, open circuit voltage and temperature of the solar panel with reference to the irradiance and temperature of Southampton. The operational parameters of REC 240-PE (under the standard conditions specified in Table 2) as obtained from its datasheet are summarized in Table 1.

Daily solar irradiance data of Southampton was acquired for all months from the European Commission website [8]. By using this data in addition to the operational parameters, I_{SC}, V_{OC} and the operational temperature of REC 240-PE were calculated via the

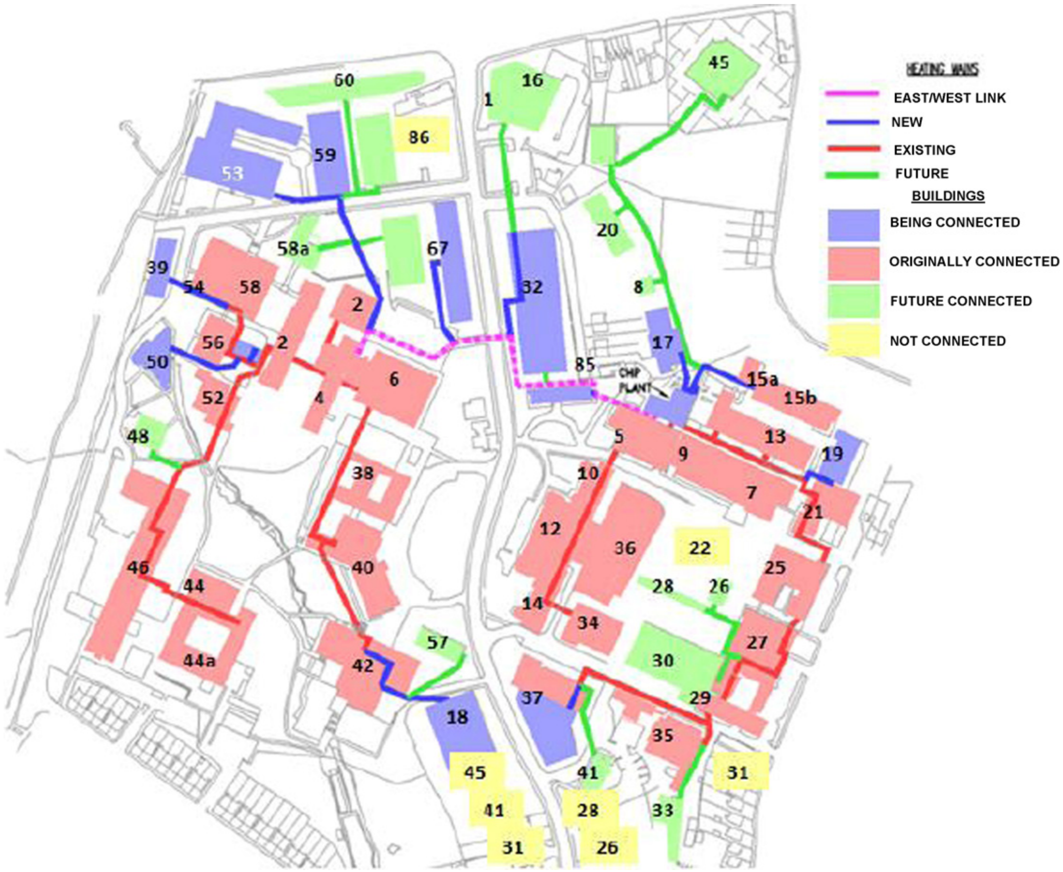

Fig. 3. CHP mini-grid for heat [7].

Table 1
Operational parameters of REC 240-PE.

Module data	REC 240-PE
Short circuit current, I_{SC}	8.4 A
Open circuit voltage, V_{OC}	37.7 V
Maximum power, P_{max}	240 W
Normal operating cell temperature (NOCT)	47.9 °C
Number of solar cells	60
Area	1.65 m^2
Efficiency	14.50%

equations below. Firstly, the operating temperature of the solar panel is calculated:

$$T_c = T_a + \left(G \times \frac{\text{NOCT} - 20}{0.8}\right) \quad (3.1)$$

where T_c is the operating temperature of the solar panel, T_a is the ambient temperature of the selected location and G is the irradiance at the respective location in kW/m^2. Secondly, I_{SC}, which depends on the irradiance of the selected location, is calculated using the following formula:

$$I_{SC}(G) = I_{SC}\,(\text{at } 1\,\text{kW/m}^2) \times G\,(\text{kW/m}^2) \quad (3.2)$$

Table 2
Standard operating conditions.

Irradiance	1 kW/m^2
Spectral distribution	AM1.5
Cell temperature	25 °C

Thirdly, V_{OC} is calculated using the cell temperature and the open circuit voltage at standard condition parameters:

$$V_{OC} = V(@SC) - (0.0023 \times N_{cells} \times (T_c - 25\,^\circ\text{C})) \quad (3.3)$$

where $V(@SC)$ is the voltage at standard conditions and N_{cells} is the number of cells in the solar module. Subsequently, The fill factor, FF, is determined as below:

$$FF = \frac{P_{max}}{I_{SC} \times V_{OC}} \quad (3.4)$$

where the values of I_{SC} and V_{OC} are at standard conditions. Finally P_{max} is determined using the following formula below:

$$P_{max}(G, T_c) = FF \times I_{SC}(G) \times V_{OC}(T_C) \quad (3.5)$$

The power of the selected PV module was calculated with the irradiance and average temperature values of Southampton taken into account. The second method involved calculating the power that the selected PV generates by using the following equation:

$$P_{max} = G \times \eta_{panel} \times A_{panel} \quad (3.6)$$

where G is the irradiance of the selected location, η_{panel} is the efficiency of the selected panel and A_{panel} is its area. This method was used to verify that the values obtained by using the first method are correct. The two methods yielded very similar results in terms of the power generated in the selected PV module. To demonstrate this, some of the calculations obtained by the first method for January are outlined in Table 3 while those obtained by the second method are outlined in Table 4. Both results were plotted on the same graph in Fig. 4 and a comparison between the two methods was carried out.

The blue line shows the outcome using the first method while the red line shows the results when the second method was used.

Table 3
January calculations using method 1.

Time	08:07	08:22	08:37	08:52
Irradiance (kW/m^2)	0.038	0.057	0.077	0.097
Average temperature (°C)		4.6		
Module performance				
I_{SC} (A)	0.3192	0.4788	0.6468	0.8148
Solar cell temperature (°C)	5.925	6.588	7.285	7.983
V_{OC} (V)	40.33	40.24	40.14	40.05
Fill factor		0.7578		
P_{max} (W)	9.76	14.60	19.68	24.73

Table 4
January calculations using method 2.

Time	08:07	08:22	08:37	08:52
Irradiance (kW/m^2)	0.038	0.057	0.077	0.097
Average temperature (°C)	4.6			
Module performance				
P_{max} (W)	9.09	13.64	18.42	23.21

Given the fact that the first method was based on more detailed calculations, it was decided to obtain the calculations based on it.

3.2.1.2. Annual energy generation potential of REC 240-PE in Southampton. Once the varying power outputs of REC 240-PE in a day for all months were obtained as explained above, the amount of potential electrical energy generation values in a day for different months were found out by finding the area under the curve of the 'power vs time' plots. For this purpose, all the power output results at the corresponding times of the day were inputted to MATLAB and plotted. For instance, the 'power vs time' graph for an average day in January in Southampton is shown in Fig. 5.

By making use of the 'trapz()' function found in the MATLAB Library, trapezoidal numerical integrations of these plots over time (i.e. the areas under the curves) were conducted. By making use of the equation Energy = Power * Time, the resultant numerical value gave the energy generation over a day in Wh.

The MATLAB variables and codes used for January are as follows:

JANpower = [...];	*input numerical power data*
JANtime = [...];	*input corresponding times of the day*
plot(JANtime, JANpower);	*plot the graph shown in Fig. 5*
JANenergy = trapz(JANtime, JANpower);	*amount of energy produced over a day*

*TOTALenergy = JANenergy*31 + FEBenergy*28 + MARenergy*31 + APRenergy*30 + MAYenergy*31 + JUNenergy*30 + JULenergy*31 + AUGenergy*31 + SEPenergy*30 + OCTenergy*31 + NOVenergy*30 + DECenergy*31;*
total annual energy generation

The daily energy generation potential of a single REC 240-PE module for various months is shown in Table 5 together with the total annual energy generation value of 284 kWh.

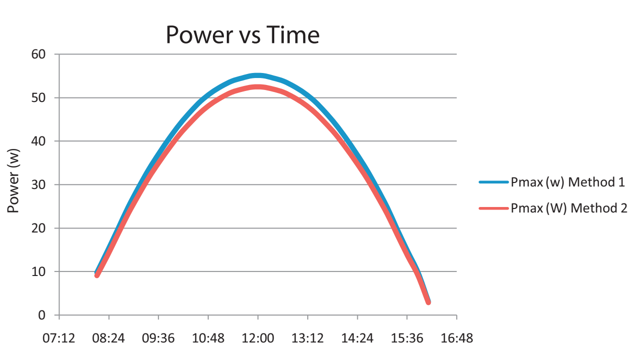

Fig. 4. Correlation between the two calculation methods.

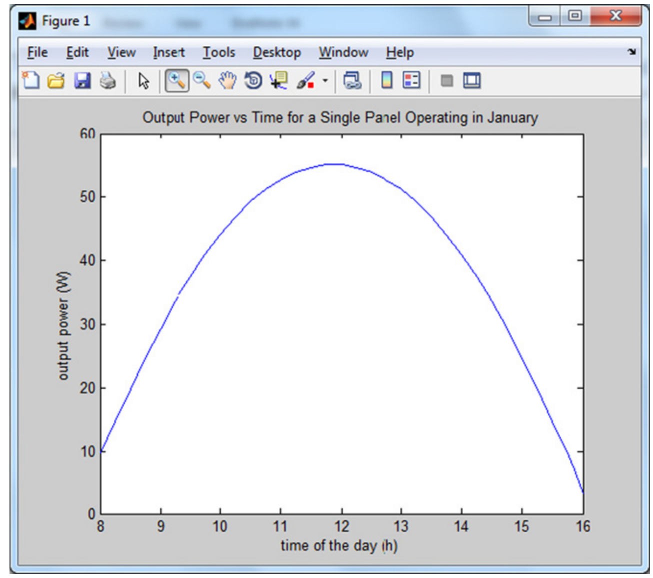

Fig. 5. Power vs time plot in January.

3.2.1.3. The final design. The monthly distribution of the electrical energy consumption of the Highfield Campus in 2009 is illustrated in Fig. 6.

Adding up the monthly values gives the total electricity consumed that year, and was found to be 35.2 GWh, as mentioned before in Section 3.1.2. The number of solar panels that is required to cover is around 134,000 panels, and this figure is enormous. Therefore, it has been decided that only 5016 panels are installed. This number was selected based on the fact that around 4% of the electrical consumption will be produced by the PV system. Hence, a total of 1.425 GWh of electrical energy will be produced each year. That is of course based on the electrical demand of the campus in 2009. Taking into account that each panel has an area of 1.65 m^2, the total area needed to place the all the solar panels is 8276 m^2. The final design also includes inverters and cable connections. Hence, more area would be required for the fitting of those components.

As mentioned before, the output voltage of the solar panels is DC and within the range of 36–40 V. Inverters are required to convert this output into 240 V AC, which is the mains electricity standard in the United Kingdom. A program known as PVSYST was used to simulate the design with inverters. After considering several inverter types, the one used in this design is Leonics GTP-535. It has an output voltage range of 125–480 V and a power value of 84 kW. The program also calculated the number of inverters required, and that

Table 5
Energy generation data for one module of REC 240PE.

Month	Average daily energy generation (Wh)	Number of days
January	307.3	31
February	524.4	28
March	729.6	31
April	1077.7	30
May	1162.3	31
June	1157.5	30
July	1179.5	31
August	1101.7	31
September	877.0	30
October	580.3	31
November	383.6	30
December	244.1	31
Total annual energy generation		284 kWh

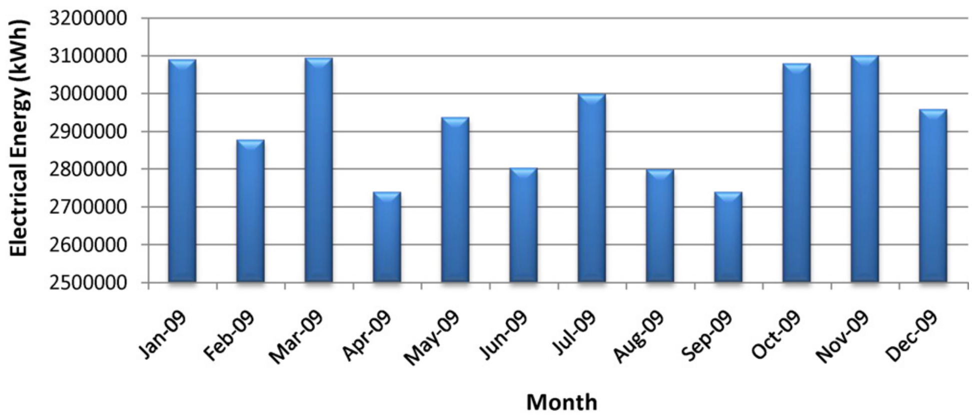

Fig. 6. Monthly distribution of energy consumption.

is 11. Finally, PVSYST an optimal orientation of the solar panels was suggested to be 11 panels in series with 456 strings making a total of 5016.

The addition of inverters and cables to contributes to energy losses. The energy losses in the cable connections cannot be estimated since their length and type are not known. However, the efficiency of Leonics GTP-535 is 93%. This means that the total energy generation per year drops from 1.425 GWh to 1.325 GWh (assuming no cable losses). This is around 3.76% of the overall annual consumption value. It is worth mentioning that the electrical energy generation capacity of the system can be increased by the addition of more solar panels and inverters if needed. The aim of this project is defined as to supply as much as possible of the annual electrical consumption by solar energy. However, due to the location of Southampton, only 3.76% of the total electrical demand was met.

3.2.2. Economical considerations

3.2.2.1. Capital cost. The distribution of cost for PV systems in general is outlined in Table 6. This distribution has been relatively stable over the last few years [9]. The price of one REC 240-PE panel provided by the manufacturing company, REC, is £336.84; therefore, by using the percentages below, the total cost of the system consisting of 5016 panels with the other components was calculated, as shown in Table 6.

3.2.2.2. Payback period. According to the UK government, starting from April 2010, feed-in tariffs are provided to people who generate their own electricity from renewable energy sources. The generation tariff is set at £0.293/kWh for 25 years for the suggested system size [10]. Therefore, the payback period is calculated below:

$$\text{Tariff income}: \quad \text{Income}_{\text{tariff}} = \text{Generated tariff} \times \text{Generated power}$$
$$= 0.293\,(\text{£/kWh}) \times 1,325,000\,\text{kWh} = 388,225\text{£} \tag{3.7}$$

Maintenance costs for each year should also be taken into account [11]:

$$\text{Maintenance cost}: \quad \text{Cost}_{\text{maintenance}} = 0.05\ (\text{£/kWh})$$
$$\times 1,325,000\,\text{kWh} = 66,250\text{£} \tag{3.8}$$

Table 6
Cost distribution in a PV panel system [9].

Component	Cost percentage	Overall system cost (£)
PV panel	66.8%	1,689,589.44
Inverter	11.7%	295,931.08
Electrical–mechanical	7.2%	182,111.44
Installation (Labor, etc.)	14.3%	361,693.55
Total	100%	2,529,326

$$\text{Annual electricity cost}: \quad \text{Cost}_{\text{electricity}} = 0.1\ (\text{£/kWh})$$
$$\times 1,325,000\,\text{kWh} = 132,500\text{£} \tag{3.9}$$

As mentioned earlier, it has to be noted that the electricity produced will be used directly. Therefore, the payback period should be found by dividing the capital cost of the system by the net profit made per year. Therefore, it is calculated as follows:

$$\begin{aligned}\text{Payback period} &= \frac{\text{Capital}_{\text{Cost}}}{(\text{Income}_{\text{tariff}} + \text{Cost}_{\text{electricity}}) - \text{Cost}_{\text{maintenance}}} \\ &= \frac{2,529,326}{(388,225 + 132,500) - 66,250} = 5.6\ \text{years}\end{aligned} \tag{3.10}$$

This means that the initial installation cost of the system will be entirely compensated after 5.6 years. After that, an annual profit of £454,475 will regularly be made, for the remaining of the 25 years. This is assuming that both the electrical consumption and the income tariff level stay the same.

3.3. Heat pump design

3.3.1. Assumptions

1. All heat transfer problems that are examined are in steady state conditions.
2. Heat transfer between the internal walls of the buildings in question is neglected.
3. Heat losses through the intermediate floors of the buildings are neglected.
4. Solar heat gains through walls and roofs of the buildings as well as ventilation heat gains in winter are neglected due to the low ambient temperature of the winter season, which is taken into account as the design environment.
5. The mean temperature of water flowing in the radiators/convectors is assumed to be 25 °C.
6. The room temperature inside the building is taken as 18 °C by considering Fig. 7. Humans can feel thermally comfortable at that temperature inside a building in winter [12–14].
7. The temperatures of all types of rooms and offices are assumed to be the same.
8. The electric heater efficiency is assumed as 1.
9. The adiabatic efficiency of the compressors of the heat pumps are assumed as $\eta_{comp} = 0.70$.
10. The adiabatic efficiencies of the gas and fuel boilers used in the buildings are assumed as $\eta_{boiler} = 0.89$.
11. All buildings in question are naturally ventilated.
12. All buildings are assumed to have intermittent shades during the day.
13. Heating will be provided for 9 months, from the start of September to the end of May.

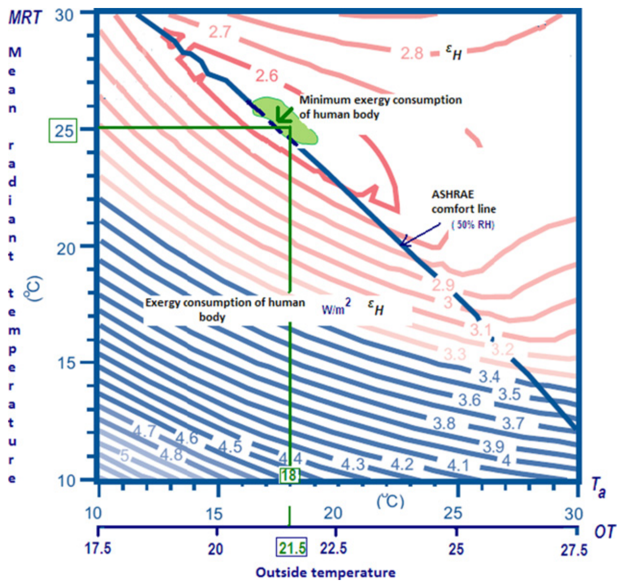

Fig. 7. Selecting inside room temperature [14].

Table 7
Southampton mean ambient temperature [17].

Temperature (°C)	Winter		Summer	
	Night	Day	Night	Day
Min	1	8	9.5	12
Max	3	9	19.5	22

Table 8
Design ambient temperature of HPs.

Temperature (°C)	Winter		Summer	
	Night	Day	Night	Day
Min	−2	7.3	16.6	23.1
Max	1.8	12.9	19.8	26.3

14. The mean soil temperature of Highfield Campus is assumed as 7 °C at a depth of 1 m [15,16].
15. The mean ambient temperature of Southampton is outlined in Table 7. The sizing of HPs is conducted by an estimation of a slightly extreme ambient temperature in Southampton. The design ambient temperature of heat pumps is outlined in Table 8 where various sources are considered in its estimation [17–19].
16. The mean coffee machine consumption is assumed as 3 cups of coffee per day per occupant.
17. The electricity used is assumed to be generated from natural gas power plants.
18. Electricity and gas prices that the university have been paying are calculated and outlined below as well as outlining the fuel price in Table 9. Prices are inclusive of VAT (17.5%) [6].
19. Electricity, gas and fuel costs are assumed to be constant throughout the lifetime of HPs.

Table 9
Monthly distribution of energy consumption.

Electricity tariff (p/kWh)	
High price period	10.1067
Low price period	6,631
Gas tariff (p/kWh)	4.56
Fuel tariff (p/l)	41.5

Table 10
Monthly heat consumption data averaged over four years.

Months	Mean heat consumption of building 1 (kWh)	Mean heat requirement of building 1 (kW)
September	1407.75	2.20
October	8376.75	12.70
November	14695.25	22.93
December	21947.25	33.10
January	22094.75	33.37
February	20189.25	33.50
March	16266.75	24.57
April	10829.75	16.90
May	4066.5	6.14

20. Daytime electricity consumption is from 7 am to 12 pm and the night-time electricity consumption is from 12 am to 7 am.
21. Maintenance and installation costs are assumed to be £100/per year and £500 respectively [20,39].

3.3.2. Technical considerations

The design solutions demonstrated in this report are the most appropriate solutions which are selected from a handful of different methods. The design solution for building 1 is selected to demonstrate the steps of design calculations.

The steps of design calculations are presented step by step below. Instead of describing the whole progress in detail, the processes that include choosing the most appropriate parameters will not be gone into detail. Instead, the chosen parameters are directly inputted into calculations. Furthermore, only the decisive processes will be described in detail. The processes are simplified so that one can follow through the steps easily and repeat them.

3.3.2.1. Heat energy requirement of buildings. Heat consumption data for the selected buildings was obtained from the metering website for the buildings for a time period of four years. Table 10 contains the average heat consumption of building 1 for every month over four years. This data is also presented visually for all the selected buildings in Fig. 8. The peaks in the graph show that maximum amounts of heat are consumed during the winter periods while it is the opposite during the summer periods. Finally, it should be noted that these buildings produce heat by means of gas boilers.

3.3.2.2. Building measurements. To ensure that the correct area values were selected for calculations further on, the area of the buildings has been found by measuring the building dimensions as shown in Table 11, either on site or by wikimapia, and calculating it. The calculated value was hence compared with the area value stated on the energy certificates and they were found to be similar. The reason for this similarity is because the taken measurements were verified to ensure that they have been measured correctly. In addition, areas of walls, etc. were needed for further calculations. As for the height, it was found that buildings either have a height of 3 m or 3.6 m.

3.3.2.3. Heat capacity calculations. To appropriately size HP, heat capacity calculations in the winter were primarily required. They consist of heat loss and heat gain calculations [20,25–28], and are calculated for building 1 below.

3.3.2.4. Heat loss calculations. Heat loss is calculated for windows, roof, front, rear and side walls between ambient air and the inside of the building. Heat losses for the floor between the soil and the inside of the building were also calculated as well as those for natural ventilation. The differences between the ambient and room temperatures, wind strength and the direction of the building are

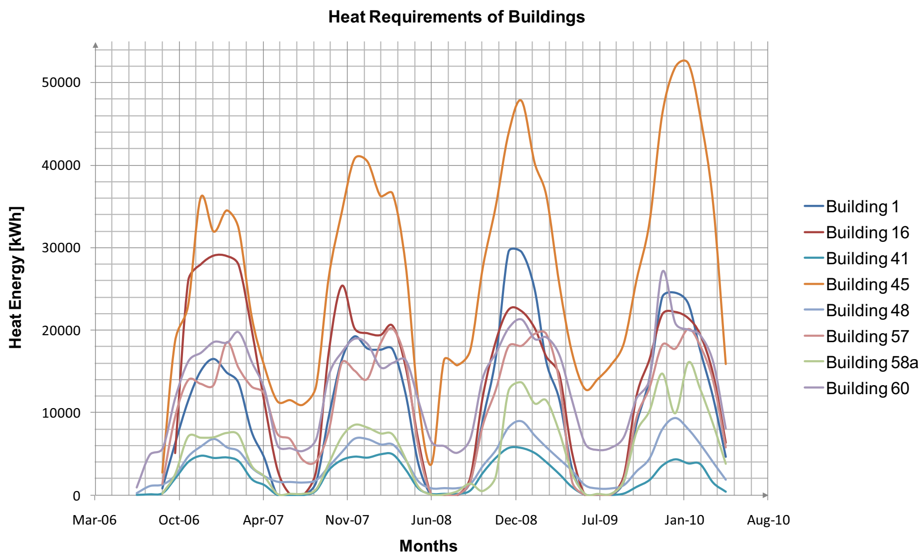

Fig. 8. Monthly heat consumption data averaged over four years [6].

Table 11
Building 1 dimensions.

The dimensions of the building 1		
Windows	Number	74
	Width (m)	0.66
	Height (m)	2.70
	Area (m^2)	1.78
Personal doors	Number	3
	Width (m)	1
	Height (m)	2.70
	Area (m^2)	2.70
Front/rear wall	Length (m)	32
	Height (m)	7
	Area (m^2)	248
Side walls	Width (m)	19
	Height (m)	7
	Area (m^2)	152
Floor/roof	Number	2
	Area (m^2)	608
	Total area (m^2)	1216
	Volume (m^3)	4256

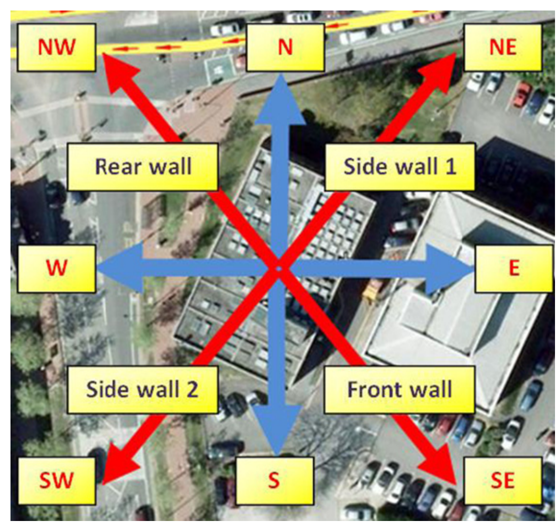

Fig. 9. Wall directions of building 1 [29].

all taken into account. The directions of the walls of building 1 are shown in Fig. 9. In addition, the heat losses portrayed in Fig. 10 are examined. Furthermore, real external air temperature can be different from the assumed value on different sides of the building. For instance, the external air temperature to the north of a building can be lower than that to the south. Thus, empirical coefficients shown in Table 13 are used in order to investigate this effect. Thermal transmittance (heat transfer) coefficients are listed in Table 12 by means of the appropriate material used, such as double glazed windows, i.e. BS EN1279. Those are mostly used in the buildings. Additionally, the number of windows is given in Table 14 for each wall. Finally, the sample calculations, which are used for each building, are presented below.

Heat loss through windows:

$$P_{windows} = N_{windows} \times U_{window} \times A_{windows} \times \Delta T = 74 \times 2.00$$

Table 12
Thermal transmittance coefficients [25,27,28].

The coefficients of thermal transmittance (W/(m^2 K))	
U_{rear_wall}	0.35
$U_{personel\_door}$	3.30
U_{front_wall}	0.35
U_{window}	2.00
U_{side_wall}	0.35
U_{floor}	0.25
U_{roof}	0.25

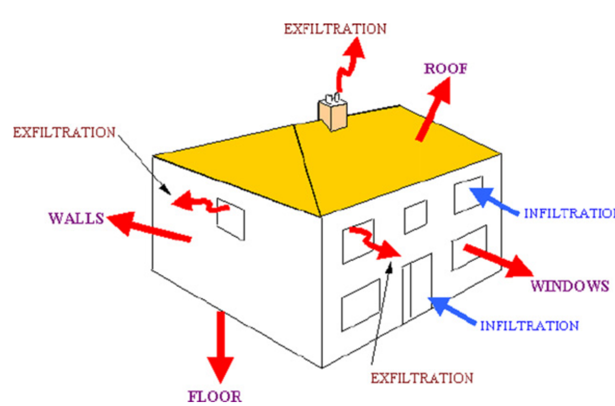

Fig. 10. Heat loss model [20].

Table 13
Monthly distribution of energy [27].

Empirical coefficients of ambient temperature	
M_{rear_wall}	1.0375
M_{front_wall}	1.0125
$M_{side\_wall\,1}$	1.0375
$M_{side\_wall\,2}$	1.0125

$$\times (0.66 \times 2.70) \times 20 = 5274.72\,\mathrm{W} \quad (3.11)$$

Heat loss through personal doors:

$$P_{p.doors} = N_{p.doors} \times U_{p.door} \times A_{p.doors} \times \Delta T = 534.6\ \mathrm{W} \quad (3.12)$$

Heat loss through the front wall:

$$P_{f.wall} = U_{f.wall} \times (A_{f.wall} - N_{f.windows} \times A_{f.windows}) \times M_{f.wall} \times \Delta T = 1398.2\,\mathrm{W} \quad (31.3)$$

Heat loss through the rear wall:

$$P_{r.wall} = U_{r.wall} \times (A_{r.wall} - N_{r.windows} \times A_{r.windows}) \times M_{r.wall} \times \Delta T = 1277.4\,\mathrm{W} \quad (3.14)$$

Heat loss through side wall 1:

$$P_{s.wall1} = U_{s.wall1} \times (A_{s.wall1} - N_{s.windows1} \times A_{s.windows1}) \times M_{s.wall1} \times \Delta T = 758.8\,\mathrm{W} \quad (3.15)$$

Heat loss through side wall 2:

$$P_{s.wall2} = U_{s.wall2} \times (A_{s.wall2} - N_{s.windows2} \times A_{s.windows2}) \times M_{s.wall2} \times \Delta T = 740.6\,\mathrm{W} \quad (3.16)$$

Heat loss through the floor:

$$P_{floor} = U_{floor} \times A_{floor} \times \Delta T_{soil} = 1672\ \mathrm{W} \quad (3.17)$$

Heat loss through the flat roof:

$$P_{roof} = U_{roof} \times A_{roof} \times \Delta T = 3040\ \mathrm{W} \quad (3.18)$$

Heat loss by natural ventilation:

$$P_{n.vent} = n \times V_{building} \times Sp.ht \times \Delta T\ Sp.ht = \frac{1000 \times C_{p,air} \times \rho_{air}}{3600} = \frac{1000 \times 1.01 \times 1.2}{3600} = 0.34 \quad (3.19)$$

$$P_{n.vent} = 1.0 \times 4256 \times 0.34 \times 20 = 28940.8\ \mathrm{W} \quad (3.20)$$

Total heat loss in building 1 $P_{total\_loss} = P_{windows} + P_{p.doors} + P_{f.wall} + P_{r.wall} + P_{s.wall1} + P_{s.wall2} + P_{floor} + P_{roof} + P_{n.vent} = 43,637\ \mathrm{W}$ (3.21)

Table 14
Number of windows.

Wall type	Direction	The number of windows
Rear wall	NW	27
Front wall	SE	15
Side wall 1	NE	16
Side wall 2	SW	16

Table 15
Mean solar gain in southeast England [25].

Months	Mean solar load (W/m^2)			
	SW	SE	NW	NE
September	197.00	202.55	97.09	101.64
October	173.64	190.91	62.36	66.27
November	147.73	170.36	29.91	30.55
December	125.73	124.55	18.00	18.00
January	130.18	146.55	26.45	26.64
February	171.18	172.73	54.36	50.73
March	199.73	198.00	97.27	97.64
April	210.91	210.73	133.36	127.64
May	202.36	198.73	157.91	153.18

3.3.2.5. Heat gain calculations. Heat gain calculations consist of solar gain through windows and internal heat gains that are produced by an estimated number of the occupants, lighting devices and electrical equipments of the buildings.

In Table 15, the mean solar load values for a building which settles in southeast England and intermittent shading during the day are demonstrated. Solar gain values are listed according to the months and the direction of the sun which will face the walls of building 1. An example of calculating the solar gain for side wall 2, which faces the southwest direction, in December is shown below:

$$\begin{aligned}(P_{sg})_{month,direction} &= S \times (q_{sg})_{month,direction} \times A_{windows} \times N_{windows,direction}\\ (P_{sg})_{December,SW} &= S \times (q_{sg})_{December,SW} \times A_{windows} \times N_{windows,SW}\\ (P_{sg})_{December,SW} &= 0.54 \times (125.73)_{December,SW} \times (0.66 \times 2.7) \times (16)_{SW} = 1935.8\,\mathrm{W}\end{aligned} \quad (3.22)$$

Similarly, the solar gain calculations for the other walls in all months were calculated, as displayed in Table 16 above. The mean solar gain of the winter months, highlighted in gray, has been found to be $P_{sg,winter,mean}$ = 5734.8 W. This is done because the HPs that are being designed should operate efficiently in the colder months.

3.3.2.6. Internal heat gains. Internal heat gains are resultant from occupants, lighting and electrical equipment inside the buildings.

Occupants:

$$P_{occupancy} = \frac{N_{floor} \times A_{building} \times P_{person}}{d_{occupancy}} = \frac{2 \times 608 \times 140}{39} = 4365.1\ \mathrm{W} \quad (3.23)$$

Lightening:

$$Index_{room} = \frac{A_{building}}{(W_{building} + L_{building}) \times H_{building}} = \frac{608}{(19+31) \times 8} = 1.52 \quad (3.24)$$

Table 16
Solar gain calculations for other walls.

Months	Actual solar gain (W)				Monthly mean total (W)
	SW	SE	NW	NE	
September	3033.11	2923.58	2616.00	1662.64	10235.33
October	2673.39	2755.62	1680.32	1084.14	8193.46
November	2274.48	2459.06	805.87	499.69	6039.09
December	1935.76	1797.71	484.99	294.46	4512.92
January	2004.34	2115.27	712.79	435.74	5268.13
February	2635.60	2493.18	1464.77	829.84	7423.38
March	3075.10	2857.97	2620.90	1597.21	10151.18
April	3247.26	3041.68	3593.33	2087.97	11970.24
May	3115.69	2868.47	4254.68	2505.86	12744.70

$$Index_{room} \rightarrow P_{density}$$
$$P_{lightening} = P_{density} \times N_{floor} \times A_{building} = 3.3 \times 2 \times 608 = 4012.8 \text{ W} \quad (3.25)$$

Electrical equipment:

$$\begin{aligned} &P_{device} = N_{device} \times P_{nameplate} \times k_{usage} \times k_{nameplate} \quad P_{computer} \\ &= 31 \times 200 \times 0.4 \times 0.7 = 1736 \text{ W} \\ &P_{photocopiers} = 2 \times 850 \times 0.1 \times 0.2 = 34 \text{ W} \quad P_{\text{modems}} \\ &= 2 \times 20 \times 1 \times 1 = 40 \text{ W} \\ &P_{coffee\_mac.} = N_{people \times} N_{coffee\_per\_person} \\ &= 84 coffee \rightarrow table \rightarrow 300 \text{ W} \end{aligned} \quad (3.26)$$

$$P_{elec.} = P_{computers} + P_{photocopiers} + P_{modem} + P_{coffee\_mac.}$$
$$= 1736 + 34 + 40 + 300 = 2110 \text{ W} \quad (3.27)$$

$$P_{internal} = (P_{occupancy} + P_{ligtening} + P_{elec.}) \times \frac{8\,\text{h}}{24\,\text{h}}$$
$$= (4365.1 + 4012.8 + 2110) \times \frac{8\,\text{h}}{24\,\text{h}} = 3496\,\text{W} \quad (3.28)$$

(8 h means that heat gain is obtained in only 8 hours of the day).

Total heat gain in building 1:

$$P_{total\_gain} = P_{sg,\text{winter},mean} + P_{\text{internal}} = 5734.8 + 3496 = 9230.8 \text{ W} \quad (3.29)$$

3.3.2.7. Total maximum heat requirement of building 1. Therefore, the heat requirement of building 1 should be as follows:

$$P_{heat} = P_{total\_loss} - P_{total\_gain} = (43637.1 - 9230.8)$$
$$\times \frac{1\,\text{kW}}{1000\,\text{W}} = 34.4\,\text{kW} \quad (3.30)$$

3.3.2.8. HP configuration and capacity decision. A simulation program for an existing HP product, Daikin Altherma, was used. This program matches the required heat pump capacities with existing HP products. The HP capacity is calculated based on the minimum night temperature and for the temperature value of water flowing from the condenser to the radiators/convectors. The results obtained include the HP performance, heating period, energy cost, CO_2 emissions, energy consumption per month, energy cost per month, thermal output by source and emitted heat per surface.

In the decision-making process of the HP configuration, two different practices were taken into consideration to meet the total maximum heat requirement of the buildings in question. The first one is meeting the demand via a large heat pump system and the second one is meeting the same demand via using a combined system of several cascaded smaller heat pumps. von Cube and Steimle [21] states that cascading smaller systems to meet the heat energy demand has a certain number of advantages, one of which is that it provides individual controlling of each HP. In the suggested design, a number of HPs are cascaded as shown to give out an overall heat output which is equivalent to the heat requirements of the buildings. When the HPs are operating at part load, an electric heater will be used to compensate for the remaining heat requirements. When the HPs are not operating at very cold temperatures, the existing gas boiler of the building will be used to provide the entire heat requirements of it. During the investigation, it has been observed that the heat capacity of a cascaded system becomes less than that when using one single HP (e.g. observed that the 12 kW ASHP model needs an additional 0.2% of electrical heat during its operation while an 18 kW unit needs 2.6%). Moreover, if one of the cascaded units malfunctions, the other units are unaffected by this and can still operate normally. In the case of building 1, the total maximum heat requirement is shared between one 11 kW unit and two 12 kW units. The simulation of one of the 12 kW units is presented below.

Table 17
Performance of alternative heating methods [30,31].

Solution type	Price per kWh (p)	Boiler efficiency	CO_2 emission factor
Gas boiler	3.8073	0.89	0.184
Fuel boiler	41.5	0.89	0.266

3.3.2.9. Inputs of the simulation programme. Firstly, the calculated required heat pump capacity, which is decided as 12 kW, is entered in "required capacity". Secondly, the total floor area, which is 1178 m^2, is entered in "surface to be heated". Thirdly, the "application" section is filled by means of design considerations as can be seen above. Fourthly, the range of temperatures is entered in "temperatures (min/max)". Fifthly, the CO_2 emission factor is entered for electricity which is generated by natural gas. Sixthly, the heating period is selected from September to end of May in terms of real heat energy requirement of the buildings. Seventhly, the electricity tariffs and day and night periods are inputted. Eighthly, the night set back temperature is inputted, which was selected as 16 °C from 7:00 am to 12:00 am. Ninthly, the zero heat pump capacity, which is the point at which the HP stops heating as it does not need to, and the minimum percentage of heat energy requirement covered by the HP are inputted. Tenthly and finally, some performance attributes of alternative heating methods are listed in Table 17 (Fig. 11).

3.3.2.10. Considerable results. Heat pump capacity. Equilibrium point, which is indicated in Fig. 12, is the point that indicates the ambient temperature at which the capacity of heat pump meets the heat energy demand. Thus, no additional heat requirement is needed above this temperature level. This point should be selected carefully. Equilibrium point is at 1 °C in this 12 kW HP design for building 1. Therefore, the backup electric heater is required for compensating the remaining of the heat requirements that the HP does not produce. The HP capacity, which is represented by the green line (to the right), is the heat energy generation capacity of the HP. The capacity is dependent on the ambient temperature and the leaving water temperature. BUH capacity (i.e. backup heater capacity), which is represented by the cyan line and is 3 kW, is the heat energy generation capacity of the electrical heater. System capacity, which is shown by the purple line, is the total heat energy generation capacity which consists of the HP and the electrical heater. It can be seen that the fluctuation of the HP capacity is associated with the variation of the outside temperature. As it is expected that such fluctuations may cause stall or chocking in the compressor due to its limited stability margin, inverters for compressor provide reliable and stable compressor operation [32]. The room temperature, therefore, will be mostly stable although the outside temperature may fluctuate even during the day. The seasonal COP of the 11 kW and the 12 kW units was calculated to be 3.7. The annual total thermal energy provided from the three units (11 + 12 + 12 kW) is outlined in Table 18 for building 1.

3.3.2.11. Energy consumption per month for each price period. Fig. 13 demonstrates the monthly heat energy consumption of building 1. The light green sections denote the daytime consumption, the dark green ones denote the night-time consumption and the blue

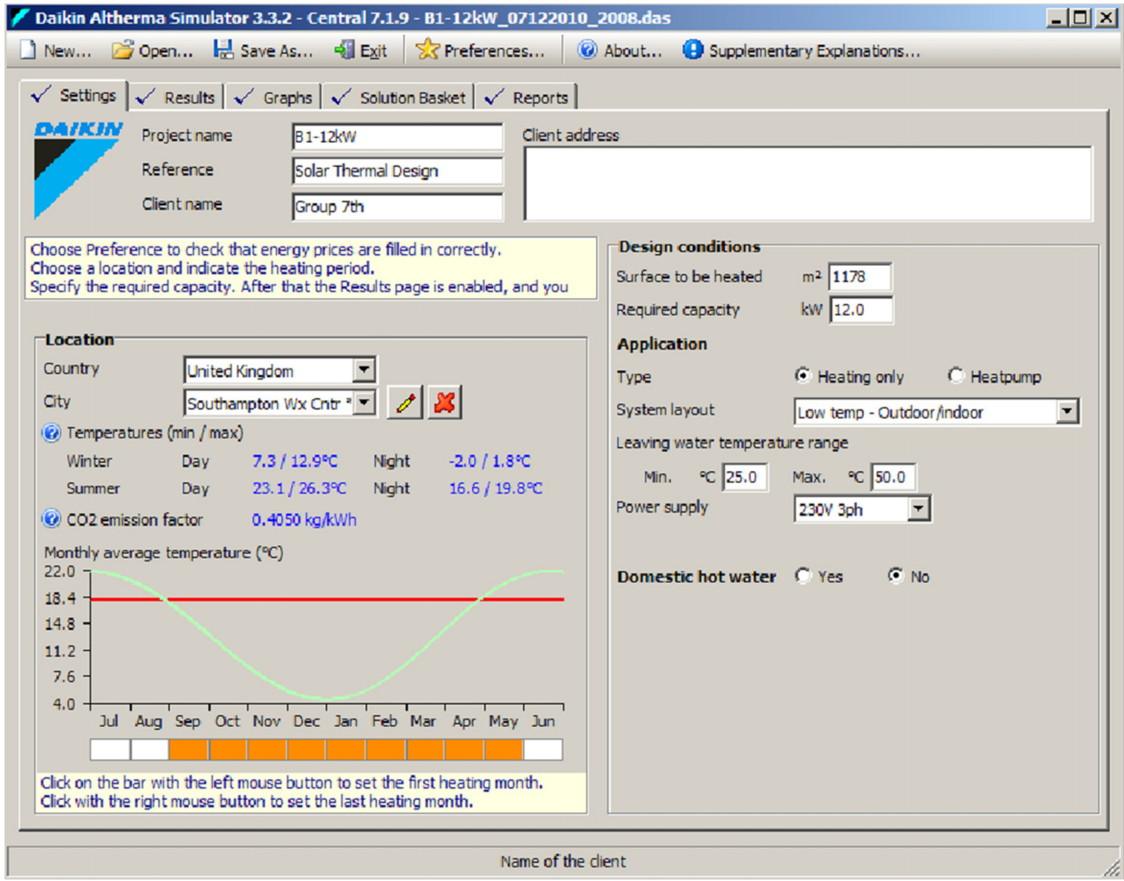

Fig. 11. Interface of the Daikin Altherma simulation program.

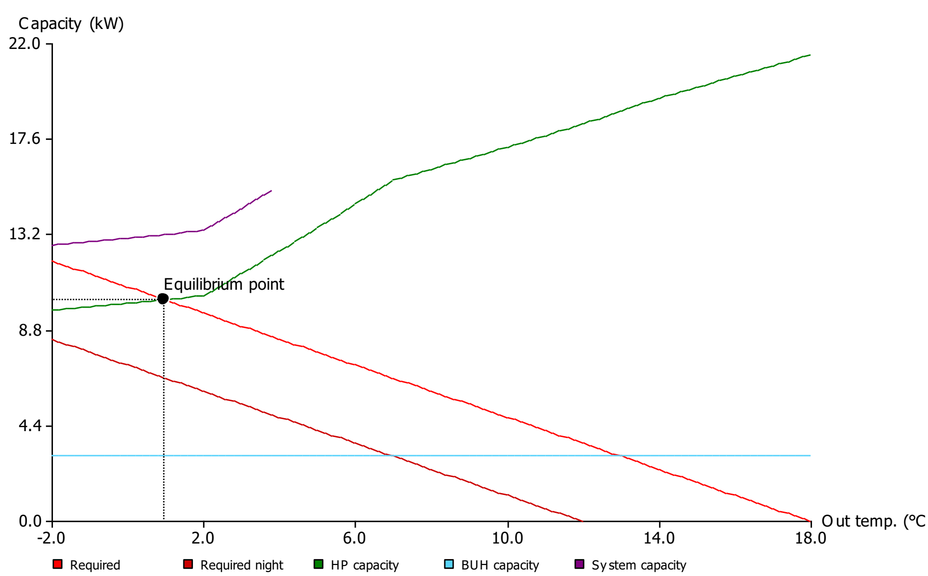

Fig. 12. Equilibrium point and capacity changes for 12 kW heat pump for building 1.

sections denote the backup consumption produced by the electrical heater. January has the highest level of heat consumption.

Table 18
Annual total thermal energy of HP System in building 1.

Annual total thermal energy (kWh)	68,449
Thermal energy from environment (kWh)	49,949
Thermal energy from electricity (kWh)	18,500

3.3.2.12. The generation of the vapour compression cycle. A program known as CoolPack was used to provide the dimensioning of a one-stage HP system that contains an evaporator, a compressor, a condenser, a throttle and the pipe lines in real-life operating conditions. The main working fluid (refrigerant) was chosen to be R134a

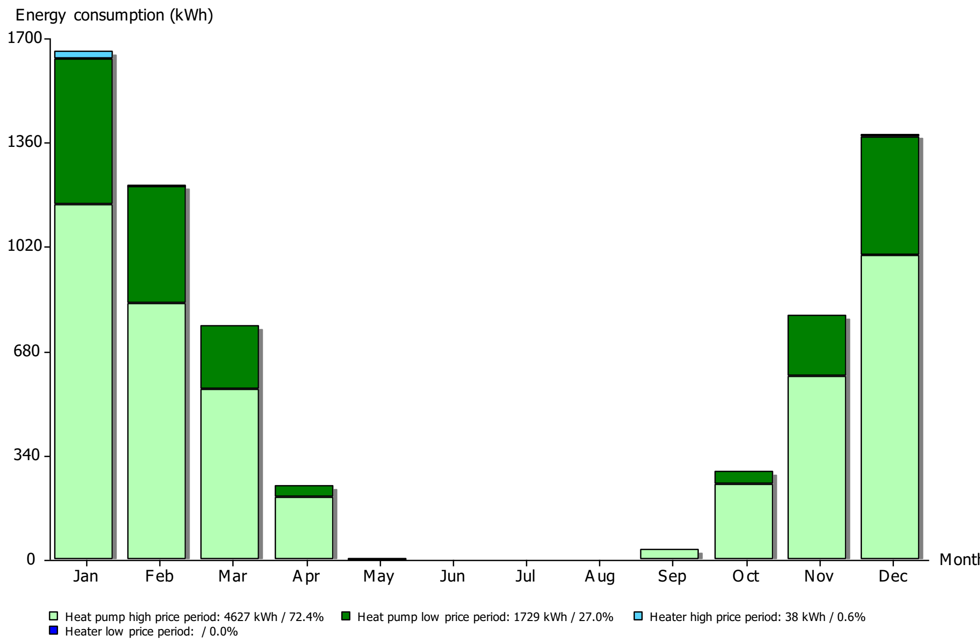

Fig. 13. Annual total thermal energy and seasonal COP of HP.

owing to the fact that it is both highly efficient and ozone-friendly. It was also favoured over other types because it was among those which cause the least amount of greenhouse gas emissions [33].

3.3.2.13. Inputs of the simulation programme. The parameters used in CoolPack are outlined in Table 19. Some principal variables are explained: firstly, the compressor discharges the refrigerant at 50 °C. Secondly, the condenser heats water up from 20 °C to 25 °C. Thirdly, the evaporator absorbs 10.18 kW of power that is combined with the compressor power from ambient air. Fourthly, the characteristics of pipes and insulations are chosen with the consideration of estimated room temperature, that is 18 °C. Some solutions generated by the simulator are interpreted next.

3.3.2.14. Considerable results. Refrigeration cycle. In the first stage, as can be seen in Fig. 14, the COP is equal to 3.7. That is the design COP. The condenser has a useful output of 12 kW. It can be noticed that pipe losses are affected by the temperature of the refrigerant. The values at the Suction Gas Heat Exchanger (SGHX) are set at zero because it is not included in the design.

Exergy analysis of components. Forming conclusions, which are regarding the efficiency of HPs, based on their efficiency found in by energy analysis can only be inadequate and misleading. Energy is analysed in a quantitative way, i.e. all the energy types are the same. It can, however, show differences in reality in the qualitative perspective. For instance, work is more valuable than heat energy and heat energy at high temperature is more valuable than that at low temperature. The reason why work is more important is related to the conversion of the work fully into heat energy. But, this cannot be realized in reverse.

Two systems having the same heating capacity are considered according to the 1st law of thermodynamics. In spite of having the same heating capacity, heat exchangers with various effectiveness values or compressors with different adiabatic efficiencies can be used in the system. In this case, the 2nd law of thermodynamics comes into action and the differences are determined. Differences can be determined by means of 2 terms: irreversibility and exergy. On one hand, irreversibility is the difference between a reversible work and useful work during a state change [34]. It shows the energy which can be converted into work theoretically but not practically. On the other hand, exergy means acquiring the maximum energy from a fluid, which has a specific energy value, by degrading it into the natural conditions [34]. These approaches help understanding and analysing a heating/cooling system and finding better and dependable solutions for sustainable energy systems. This is because these terms clearly reveal how much exergy is supplied to a system along with where and how it is used in the system. The main components of HP systems, namely the compressor, the evaporator and the condenser are investigated in terms of exergy below [35,36].

Exergy analysis of compressor (Table 20)

$$\psi = (h - h_0) - T_0(s - s_0) \tag{3.31}$$

$$W_{rev} = \psi_i - \psi_e \tag{3.32}$$

$$w_{in,\min} = \psi_2 - \psi_1 = (h_2 - h_1) - T_0(s_2 - s_1) \tag{3.33}$$

$$w_{in,actual} = (h_2 - h_1) \tag{3.34}$$

$$\begin{aligned} \eta_{II} &= \frac{w_{in,\min}}{w_{in,actual}} = \left(\frac{(h_2 - h_1) - T_0(s_2 - s_1)}{(h_2 - h_1)}\right) \\ &= \left(\frac{(282.9 - 251.2) - 271.83(1.77385 - 1.7723)}{(282.9 - 251.2)}\right) \\ \eta_{II} &= 0.99 \end{aligned} \tag{3.35}$$

$$\begin{aligned} i &= w_{in,actual} - w_{in,\min} = T_0(s_2 - s_1) = 271.83(1.77385 - 1.7723) \\ &= 0.42\ \mathrm{kJ/kg} \end{aligned} \tag{3.36}$$

Exergy analysis of evaporator (Table 21)

$$\begin{aligned} \eta_{II} &= \left(\frac{(h_9 - h_8)}{(h_9 - h_8) - T_0(s_9 - s_8)}\right) \\ &= \left(\frac{(250.5 - 83)}{(250.5 - 83) - 271.83(1.58523 - 1.55873)}\right) = 0.72 \end{aligned}$$

$$i = T_0(s_9 - s_8) = 271.83(1.58523 - 1.55873) = 7.20\ \mathrm{kJ/kg}$$

Exergy analysis of condenser (Table 22)

$$\eta_{II} = 0.55,\ i = -173.3\ \mathrm{kJ/kg}$$

Table 19
Annual total thermal energy and seasonal COP of HP.

Compressor variables		Liquid line 1 for T_{AIR} = 18 °C RH_{AIR} = 40%	
Compressor efficiency	0.7	Pipe material	Copper
Discharge temperature	50	Velocity (m/s)	0.6
Condenser variables		Length (m)	10
T_D (K)	10	Insulation of liquid line	Yes
Subcooling (K)	5	Insulation material	Armaflex
Condenser type	Water cooled	Insulation thickness (mm)	10
Inlet temperature (°C)	20	Liquid line 2 for T_{AIR} = 18 °C RH_{AIR} = 40%	
Heating of secondary fluid (K)	5	Pipe material	Copper
Radiant temperature °C)	25	Velocity (m/s)	0.6
Evaporator variables		Length (m)	10
Refrigerating capacity (kW)	10.18	Insulation of liquid line	Yes
T_D (K)	9	Insulation material	Armaflex
ΔT_{SH} (K)	12	Insulation thickness (mm)	15
Evaporator type	Air cooler	Suction line for T_{AIR} = 18 °C RH_{AIR} = 40%	
Inlet temperature (°C)	−2	Pipe material	Copper
Cooling of secondary fluid	3	Velocity (m/s)	10
SHR (%)	80	Length (m)	10
Pipe variables		Insulation of liquid line	Yes
Discharge line		Insulation material	Armaflex
Pipe material	Copper	Insulation thickness (mm)	25
Velocity (m/s)	12		
Length (m)	10		
Insulation of discharge line	None		

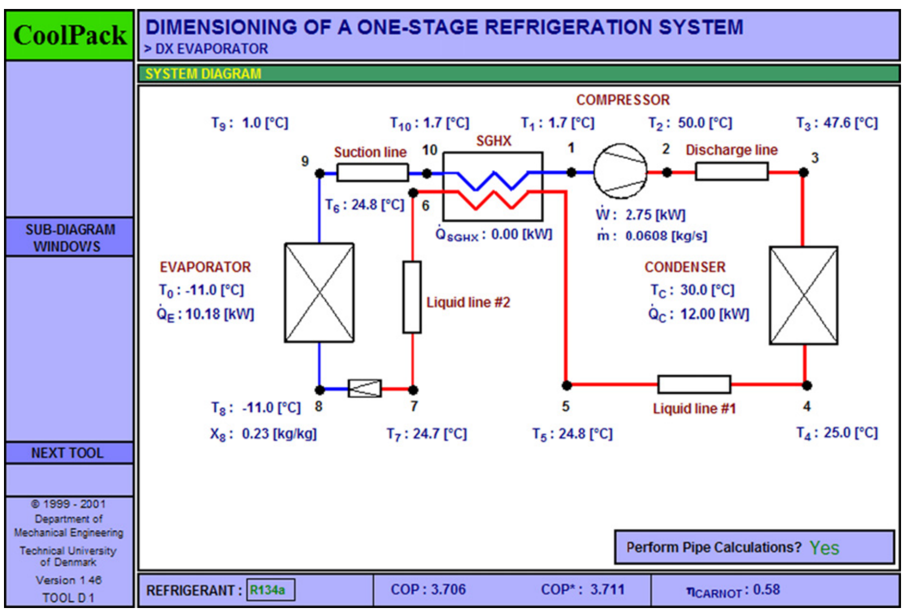

Fig. 14. Refrigeration (vapour compression) cycle of designed system.

Table 20
Compressor inlet/outlet parameters.

Standard		Inlet		Outlet	
P (kPa)	100	P_1 (kPa)	190	P_2 (kPa)	798.2
T (K)	298.15	T_1 (K)	275.08	T_2 (K)	323
h_0 (kJ/kg)	424.34	h_1 (kJ/kg)	251.2	h_2 (kJ/kg)	282.9
S_0 (kJ/(kg K))	1.90058	S_1 (kJ/(kg K))	1.7723	S_2 (kJ/(kg K))	1.77385
v_0 (m^3/kg)	0.2378	v_1 (m^3/kg)	0.1111	v_2 (m^3/kg)	0.0285

Table 21
Evaporator inlet/outlet parameters.

Standard		Inlet		Outlet	
P (kPa)	100	P_8 (kPa)	192.9	P_9 (kPa)	192.9
T (K)	298.15	T_8 (K)	262.38	T_9 (K)	274
h_0 (kJ/kg)	424.34	h_8 (kJ/kg)	83	h_9 (kJ/kg)	250.5
S_0 (kJ/(kg K))	1.90058	S_8 (kJ/(kg K))	1.55873	S_9 (kJ/(kg K))	1.58523
v_0 (m^3/kg)	0.2378	v_8 (m^3/kg)	N/A	v_9 (m^3/kg)	0.1075

Table 22
Condenser inlet/outlet parameters.

Standard		Inlet		Outlet	
P (kPa)	100	P_3 (kPa)	770.6	P_4 (kPa)	770.6
T (K)	298.15	T_3 (K)	320.98	T_4 (K)	298
h_0 (kJ/kg)	424.34	h_3 (kJ/kg)	280.9	h_4 (kJ/kg)	83.4
S_0 (kJ/(kg K))	1.90058	S_3 (kJ/(kg K))	1.77009	S_4 (kJ/(kg K))	1.13246
v_0 (m^3/kg)	0.2378	v_3 (m^3/kg)	0.0293	v_4 (m^3/kg)	0.0008

3.3.3. *Economical considerations*

3.3.3.1. *Energy costs.* The operating energy cost of HPs in building 1 compared to the other heating alternatives is shown in Table 23.

3.4. *Material and installation costs*

The cost of a Daikin Altherma heating only air sourced heat pump kit is taken into account [37]. The cost of a single kit is £7721 excluding VAT. The kit includes the following:

Components inside the kit
1 × Daikin ERHQ016BA Absorber outdoor unit
1 × Daikin EKHBH016BA3V3
1 × Daikin EKUHWB (INSTALLATION ACCESSORY KIT)
16 Meters of cable for interconnecting cable
15 Meters of insulation and pipes
1 × Wall bracket for condensing unit
1 × 3 phase 3 kw heater
3 × Wired controller

The installation and maintenance costs are estimated at £500 and £100/year respectively.

3.4.1.1. *Cost analysis*

Two cost analyses are obtained. One is for building 1 only; the other one is for whole systems. The main reason why two cost analyses are provided is because different renewable heat tariffs are provided by the government. The tariff for ≥45 kW systems is 7.5 p/kWh for 18 years, while it is 2 p/kWh for 20 years in the case of 45–50 kW systems. The cost analysis procedure is described below [38]:

$$\text{Payback ratio (years)} = \frac{\text{Total capital cost (£)}}{\text{Annual average return (£/year)}} \tag{3.37}$$

$$\text{Total captial cost (£)} = \text{Material cost (£)} + \text{Installation cost (£)} \times (1 + \text{VAT (\%)}) \tag{3.38}$$

$$\text{Annual average return (£)} = \text{Electricity cost} + \text{Annual maintenance cost [£]} = (\text{Incentive (£/kWh)} \times \text{Annual thermal energy produced (kWh)}) \tag{3.39}$$

$$\text{Total income after payback [£]} = (\text{Lifetime of heat pump} - \text{Payback ratio})\,\text{(years)} \times \text{Annual incentives (£/year)} \tag{3.40}$$

The parameters and results of cost analysis of heat pumps (11 + 12 + 12 kW) for building 1 are shown in Tables 24 and 25. In Table 25, the payback ratio is presented with cash flow due to the incentive until the end of the heat pumps.

Table 23
Energy cost for different heating systems.

	Heat pump	Gas boiler	Fuel boiler	Elec. heater
Energy cost (p)	171,147	350,706	309,878	640,506

Table 24
Cost analysis input parameters, building 1.

VAT (%)	17.5
Installatin cost (£)	500
Material cost (£)	27717
Total capital cost in, VAT (£)	27804
Annual maintenance (£/year)	100
Lifetime of hear pump (years)	18
Heat pump energy cost (£)	1711
Incentive (p/kWh)	7.5
Annual heat energy (kWh)	68449
Annual income (£)	5034
Heat pump energy cost after incentive (income) (£)	−3322

Table 25
Cost analysis results, building 1.

	Gas boiler	Fuel boiler	Elec. heater
Payback ratio (years)	4.07	4.33	2.86
Total income after payback (£)	71505.39	70176.41	77732.26

Table 26
Cost analysis input parameters, all the selected buildings.

VAT (%)	17.5
Annual maintenance (£/year)	1000
Total capital cost inc. VAT (£)	259896
Lifetime of hear pump (years)	20
Incentive (p/kWh)	2.0
Annual heat energy (kWh)	700136
Annual income (£)	13003
Heat pump energy cost after incentive (£)	4219

Table 27
Cost analysis results, all the selected buildings.

	Gas boiler	Fuel boiler	Elec. heater
Payback ratio (years)	8.45	9.74	4.36
Total income after payback (£)	161710.33	143651.87	219042.93

The parameters and results of the HP cost analysis for all the selected buildings are shown in Tables 26 and 27. From an investor's point of view, the suggested design reveals that they are highly capital intensive. With current market prices, conventional methods of heating seem affordable. Subsidized heat pumps, however, provide a competitive advantage as can be seen in Table 27.

3.4.2. *Environmental considerations of heat pumps*

Future efforts in heating conversion systems should focus not only on reducing capital and operation costs but also on the amount of emissions it reduces, such as CO_2 emissions. In Table 28, emission values of HPs operating in building 1 (11 + 12 + 12) are compared with that of gas boilers, fuel boilers and electrical heaters. As it is clear from Table 29, heat pumps are the best environmental choice.

Table 28
Carbon emissions for building 1.

	Heat pump	Gas boiler	Fuel boiler	Elec. heater
CO2 emission (ton/year)	7.6	14.2	20.4	27.7

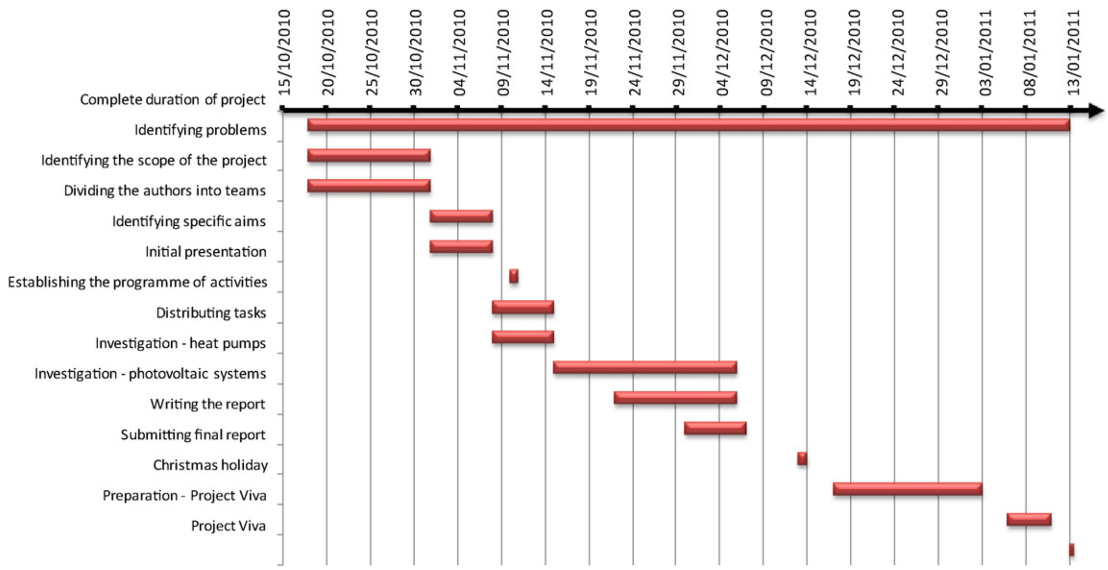

Fig. 15. Gantt chart.

In Table 29, where all the selected buildings are taken into consideration, it can be seen that the overall emission level of the HPs is approximately 3.5 times less than electrical heaters, which is most commonly used in Southern England.

4. Discussion

The performance and feasibility of the installation of a PV system to cover as much as possible from the electrical demand of the campus was investigated. It was found that the system proposed is capable of providing only 4% of the electrical demand. This low value is primarily due to the fact that the irradiance levels in Southampton are simply not high enough. This is backed up by the fact that in July, which has the highest levels of irradiance, only 84.5 W of peak power is generated by a single panel. This is significantly low when compared with the theoretical peak power output that the panels are capable of generating. Another factor that contributes to this low generation of electricity is that in the design, the panels are fixed at a certain inclination. Therefore, they cannot optimally capture energy at all times, as the position of the earth with respect to the sun keeps on changing continuously throughout the day. From an environmental point of view, this system can contribute to a reduction of 536.63 tons from the overall CO_2 emissions produced by the campus [6]. Reductions in CO_2 emissions are always encouraged. However, this amount is only a fraction when compared to the overall emissions produced by the whole campus.

The initial cost of the PV system was found to be £2,529,326. In addition, it has a payback period of 5.6 years. This number is very good considering the fact that the PV panels only cover 4% of the total electricity demand of the campus. Moreover, the system will still generate a net profit of £454,475 for the remaining 19.4 years, which totals to £8,816,815. This calculation was based on the fact that the university already has a piece of land somewhere nearby that is optimal for the installation of the PV panels. Most likely this is not the case; therefore, if the cost of buying a piece of land was added to the capital cost, this will significantly increase the payback period.

Table 29
Carbon emissions for all the selected buildings.

	Heat pump	Gas boiler	Fuel boiler	Elec. heater
CO2 emission (ton/year)	75.4	140.3	202	274

The performance and feasibility of installing a HP system that is responsible for covering the heat demands in selected buildings was also investigated. The minimum operating temperature of the HPs is −2 °C. This means that the HP system will not be operating below this value. This value is ideal considering the extreme climate conditions of Southampton over the last 30 years. Although the COP of air source HPs decreases when the outside air temperature decreases, the seasonal COP of the suggested systems for the selected buildings was found through both programs to be around 3.7. Considering that this is the average COP for the coldest three months of the year, with which the design calculations were based on, it is expected to be higher for the other months. The amount of heat energy produced annually by the HP system in building 1 was found to be 68,449 kWh. In contrast, the mean amount of heat energy produced over four years by the gas boiler in building 1 was calculated to be 119,874 kWh. Therefore, the amount produced by the HP system seems to be around 57% of that produced by the gas boiler. This is chiefly because the HPs in the design do not operate below −2 °C and above 18 °C. One more factor that affected this result is the temperature input in the Daikin Altherma program. It was found by averaging the temperatures of the three coldest months for a period of 30 years. Therefore, it is expected that those temperature values are not closely correlated with each other. However, it is the opposite case for the calculation of the heat energy produced by the gas boiler, which was based on consumption values for the past four years.

From an environmental perspective, the HP design for all the selected buildings contribute to a reduction of 75.4 tons of greenhouse gas emissions per year. This figure is significantly smaller than the CO_2 emissions produced by other heating alternatives, as has been mentioned before. However, it has to be outlined that the dependence on electric heaters has to decrease in the UK because they contribute to the highest amount of emissions, which is 274 tons per year. Finally, the overall cost of the HP system for the selected buildings was found to be £259,896. The payback period for all the buildings was calculated based on the fact that the existing heating systems are gas boilers, fuel boilers or electric heating. The payback period for all buildings assuming they have gas boilers was the highest, with 8.45 years, where those utilizing electric heating was the lowest, with 4.36 years. Overall, the payback period

Table 30
Work distribution.

Section	Author(s)	Section	Author(s)
1	Izzat	3.2.2	Angeliki, Eleni
2.1	Angeliki, Eleni	3.3	Kutalmis
2.2	Izzat	4	Everyone
3.1	Naci, Ozcel	5	Magdoom, Mario
3.2.1	Mario, Ozcel,	Naci, Magdoom	6 Eve
Report assembled by Izzat			

is still sensible and a generous profit following the remaining of the tariff years is still generated by using anyone of the existing heating systems.

5. Project management and planning

Like any project is initiated, the starting point of this project was by identifying the requirements and making sure that they are clear for everyone. Energy consumption data was obtained from two sources in order to give the authors an idea of the consumption in the campus. Based on this data, several sustainable methods/system types were brainstormed and analysed from different aspects, such as efficiency, cost and dependence on the geographical location. This has helped the authors eliminate the impractical ones and settle on two systems: photovoltaic systems and heat pumps. It was initially intended to design systems that can provide the total energy consumption of the campus; however, this was not possible as the infrastructure of the campus is old and cannot be rendered to new adjustments easily. Therefore, the main objective of making the campus more sustainable was set. Specific objectives were set later on and the authors split up into two teams, one working on PVs, which included Mario, Eleni, Angeliki, Magdoom, Naci and Ozcel, and the other on HPs, which included Kutalmis and Izzat. Each team did an in-depth analysis about the systems and suggested a design. At the end, the different sections of this report were written, assembled and reviewed. The authors' contribution to the different sections of the report and a Gantt chart for the progress of the project, are shown in Table 30 and Fig. 15.

6. Conclusion

This project has investigated the technical and feasibility aspects of designing an off-grid PV system that is capable of generating as much as possible of the electrical demands of the Highfield Campus. Similarly, an air source HP system has also been designed for selected buildings to be able to supply them with their heating demands. The design process included establishing a basic understanding of PVs and HPs and the way they operate. In addition, energy consumption data of the Highfield Campus was crucial for both knowing how much energy the relevant buildings consume and for designing both systems.

The PV system design involved selecting an efficient PV panel type. By using the irradiance data for Southampton, the power output of the whole system, which contains 5016 panels, has been found to be 1.325 GWh and that is approximately 3.76% of the annual electrical demands of the campus. If this value is looked at separately, one would say that the system is not efficient because it is a fraction of the total electrical demand. Also, the operation of PV systems does not contribute to any emissions. On the contrary, they should reduce the overall emissions produced by the campus; but because only a fraction of the total electrical demand is generated, the amount of CO_2 emissions is not reduced by much when compared to the total amount. When the costs of the system, however, are taken into account, it appears that this system is worth investing in, from an investor's point of view. This is because its payback period, 5.6 years, is relatively small. Of course this applies if the investor already has an area for the installation of the system. Nevertheless, the system will still yield a net profit at the end even if an area has to be purchased. The profit will not be as significant as in the first case, but it will also be more or less worth the investment.

The HP system design involved the calculation of the net heat losses in each building and sizing an appropriate cascaded system that consists of smaller accordingly cascaded units. The HP system operates at an ambient air temperature range of −2 °C to 18 °C and provides at least 80% of the heat demand when in operation. For building 1, the heat energy was calculated and it was shown before that this heat was sufficient to heat the building when the HP was working. HPs have a notably lower environmental impact than that of other heating alternatives, as they release considerably lower amounts of CO_2 emissions per year when compared to their competing systems. Finally, the system can be considered as a good investment because the capital cost and the payback periods are relatively moderate.

The PV system has moderate performance efficiency and does not result in substantial emission reductions in relative to the total emissions figure. However, results have shown that this system is a good investment, as it will start producing profit after a specified time period. In contrast, The HP system has a very good efficiency and results in substantial emission reductions when compared with the existing heating systems. At the moment, HPs cannot be considered as fully sustainable because the production of the electricity used to operate them results in emissions. However, if the electricity comes from a renewable source, then HPs can be deemed as fully sustainable. Results have also shown that this system is feasible and will start making profit after a specified time period. One last thing to point out is that the production of both PVs and HPs consumes energy; therefore, resulting in carbon emissions. If they are manufactured and used more commonly, then manufacturers will have to think of more energy-efficient methods to reduce the energy consumption throughout the manufacturing process; hence, reducing the amounts of CO_2 emissions resulting from their production processes. Taking all the previous points into account, it can hence be concluded that both PVs and HPs are suitable solutions in terms of the impact they have on reducing the overall amount of emissions of the campus and that both of them are regarded as feasible systems since they both contribute to considerable amounts of net profit.

The systems, as they stand, are considered to be good and efficient. However, general suggestions and specific recommendations for the energy consumption of the campus and for both systems are suggested to further improve their performances. Regarding general suggestions, if more awareness regarding energy saving was encouraged among students and staff, significant amounts of energy would be saved. In addition, better monitoring of the consumption values can help obtain more accurate results. Improvements for the PV system design include using monocrystalline panels instead of polycrystalline panels owing to their higher efficiency, employing a solar tracking system to the panels as this increases their power output by about 30% [40] and, if possible, increasing the number of panels in order to capture and generate more energy. Improvements for the HP system design include employing multi-stage cycles [2]. Those can be multi-compression, multi-evaporation or even cascading in such a way that one HP's condenser is another HP's evaporator. All of those result in obtaining higher efficiencies. Other improvements include using new types of compressors that consume less electricity and refrigerants that are both efficient and environment friendly. A hybrid desiccant HP system is suggested. This system absorbs humidity and therefore eliminates the energy required to either over-cool or over-heat to eradicate the effects of humidity. Finally,

if enough space was provided, ground source HPs would be preferred over air source because they are more efficient and more reliable as the soil temperature remains more or less constant [41].

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